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Burcharth, Hans F.

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Michael Brorsen

Hans F. Burcharth

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AALBORG UNIVERSITETSCENTER
LABORATORIET FOR HYDRAULIK OG HAVNEBYGNING
SOHNGÅRDSHOLMSVEJ 57 DK-9000 AALBORG DANMARK

Hans F. Burcharth

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May 1983

Seminar on Rubble Mound Breakwaters, Stockholm, Sweden.

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Hans F. Burcharth
Institute of Civil Engineering
Aalborg University Denmark

INTRODUCTION

1. Stone and concrete are two materials generally used for the construction of rubble mound breakwaters. This paper deals with concrete only. Concerning stone and rock reference is given to the following paper by A.B. Poole, P.G. Fookes, T.E. Dibb, and D.W. Hughes: Durability of rock in breakwaters. Proc. Conference on Rubble Mound Breakwaters, Inst. of Civil Engineers, London, May 1983.

2. It is shocking to know that only a few years ago very few breakwater designers thought about the mechanical stability or the strength of the armour units. The designs were based purely on hydraulic model test results and the design criterion was chosen with consideration only to the hydraulic stability. A typical criterion was (and still is) a few percentage, say 2-5%, of the armour units displaced in the design storm. The stresses in the units were not considered and for this reason no attempt was made to measure the stresses in the units, neither directly or indirectly.

   When one realises that nearly all concrete armour units including the slender complex ones like Dolosse are made of unreinforced concrete, one might wonder what coastal engineers have been thinking of. In the laboratory model units never break due to wave action because all materials traditionally used are relatively far too strong to represent concrete in a correct scale.

OBJECTIVES IN ARMOUR DESIGN

3. From a hydrodynamic point of view we want a permeable armour layer. This generally means as little concrete as possible per unit volume of the armour layer, resulting in slender types of units. This is in agreement with the wish of saving material and of reducing the weight of the individual unit.

   However, we also want a low cost material, a simple production procedure, and a robust unit, which can stand rough treatment during handling and placement and which exhibits a good long term durability.

   Unfortunately these two sets of aims and wishes are very much contradictory. The outcome will, therefore, (with the present technology) always be compromises.

STATE OF THE ART

4. The state of the art in armour unit design procedure can be briefly described as follows:

   1. The loads are, with a few exceptions, only known qualitatively.
   2. The units' response to certain deterministic loads is known, partly from theory, partly from full scale physical tests.
   3. The theories for the material response are not able to explain reactions to all the loads of importance.

   It follows that a consistent design procedure can be obtained only if a lot more is known, especially about the loads.

TYPES OF LOADS

5. The different types of loads on armour units and their origins might be listed as follows:

TYPES OF LOADS		ORIGINS OF LOADS
STATIC		Weight of units Prestressing due to: Settlement of underlayers Wedge effect and arching due to movements under dynamic loads
ABRASION		Suspended material
DYNAMIC	Impact	Rocking/rolling of units Missiles of broken units Placing during construction
	Pulsating	Earthquake Gradually waving forces
THERMAL		Stresses due to temperature differences during hardening process Freeze-thaw
CHEMICAL		Corrosion of reinforcement Sulfate reactions etc.

Types of loads

If we relate the loads to the types of armour units it is clear that for the slender complex types of units the dynamic and the static loads are the critical ones, while for bulky units it is dynamic and thermal loads that are critical.

GENERAL DISCUSSION OF STATIC AND DYNAMIC LOADS ON SLENDER COMPLEX TYPES OF UNITS

6. It is characteristic for both static and dynamic load conditions that a deterministic calculation of the stresses in the units is practically impossible, mainly because of the randomness of the ways in which the units are supported and because of the difficulties in determining the actual wave forces. It is also characteristic that the stresses will increase with the size of the units, other things being equal. Roughly it can be said that the stresses due to static loads are proportional to the characteristic length while the stresses due to impact loads are proportional to the square root of the characteristic length.

Although the stresses from static loads are thus the fastest growing, it is not known at the moment which of the two types of loads are the most dangerous to big units. This is so partly because the actual levels of the two loads are not known and partly because the two types of loads cannot be separated in general, as they interact. The dynamic impact loads are absolutely dominating for the exposed units sitting freely in the top layer of the armour, thus having greater chance of rocking or even rolling up and down or being hit by fractions of other units. But on the other hand, if the units are not moving and missiles non-existent it is obvious that only static and pulsating dynamic loads are present. The latter holds for many units in the bottom layer of conventionally designed armours and also for all units in armour layers where a conservative »no-movement« hydraulic stability criterion is used.

Since the complex units for a good deal rely on the prestressing, which can be obtained on steep slopes by the weight of the units, it is clear that some units must carry load transferred from several other units in the pack. If we look at a deepwater breakwater with big unreinforced Dolosse, say 30-50t, on a 1 in 1.5 slope it can be shown by rough calculations that some of the units are likely to fail due to static load from gravity only. But again in order to make reliable calculations on static load stresses we need a theory on load-distribution in a granular pack (a corn-flakes theory).

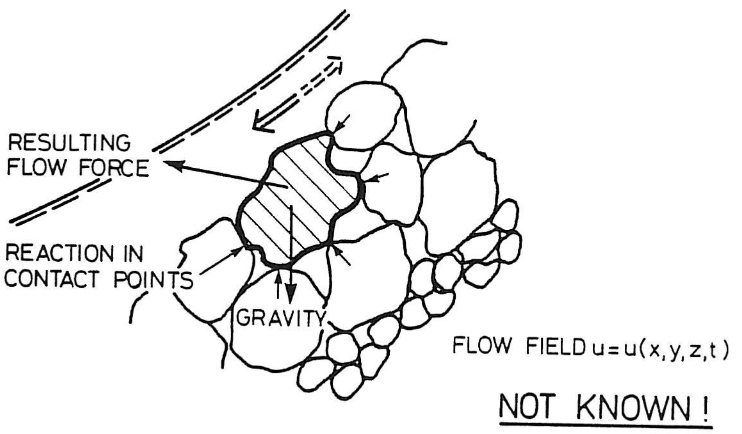
METHODS FOR THE ASSESSMENT OF STATIC AND DYNAMIC LOADS

7. For the assessment of the static and the dynamic loads the following methods can be applied:

    1. Analytical approach based on basic principle theories (computer models)
    2. Similarity methods
    3. Model tests
    4. Prototype recordings

    In practise the methods will, of course, be combined.

8. ad. 1. The difficulties related to the purely theoretical approach might be illustrated by considering the forces on an armour unit.



GRAVITY : $F_G \approx g\rho_w\left(\frac{\rho_s}{\rho_w}-1\right)d^3$

FORM DRAG: $F_{D,F} \approx C_F\, \rho_w\, d^2|u|u$

SURFACE DRAG: $F_{D,S} \approx C_S\, \rho_w\, d^2|u|u$

LIFT: $F_L \approx C_L\, \rho_w\, d^2 u^2$

INERTIA, FROUDE-KRYLOV: $F_I \approx C_I\, \rho_w\, d^3 u'$ (pressure grad. undisturb. flow)

INERTIA, ADD. HYDRODYN. MASS: $F_H \approx C_M\, \rho_w\, d^3 u'$ (change of flow field by the body)

COEFFICIENTS C are functions of Keulegan-Carpenter No. and Re No. and will vary considerably in time.

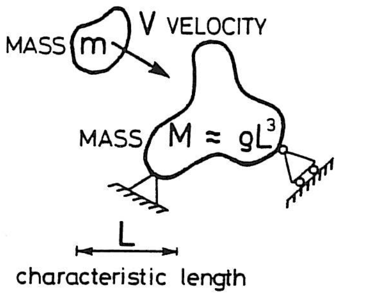
Forces on armour unit

Steps in direction of purely analytical treatment are mathematical models by Austin et al. (ref. 1) and Barends et al. (ref 2). Calibration of the models against prototype data is a necessity.

9. ad. 2. When theoretical models based on basic principles are not possible, a similarity model might be used. Burcharth tried this method with the objective of establishing a design method by which both hydraulic and mechanical stability of armour units are linked (ref. 3, 4, 5).

The method can be illustrated by the application on slender complex types of units sitting freely in the top layer of the armour and therefore exposed to impact loads mainly.

By considering a class of geometrically similar systems we can, as shown below, arrive at an expression for the dimensionless stress in impact loaded units.



E elastic modulus
ν Poisson's ratio
ρ mass density

$\simeq$ constants, i.e. rate of strain on stress is neglected.

By dimensional analysis we obtain the dimensionless stress:

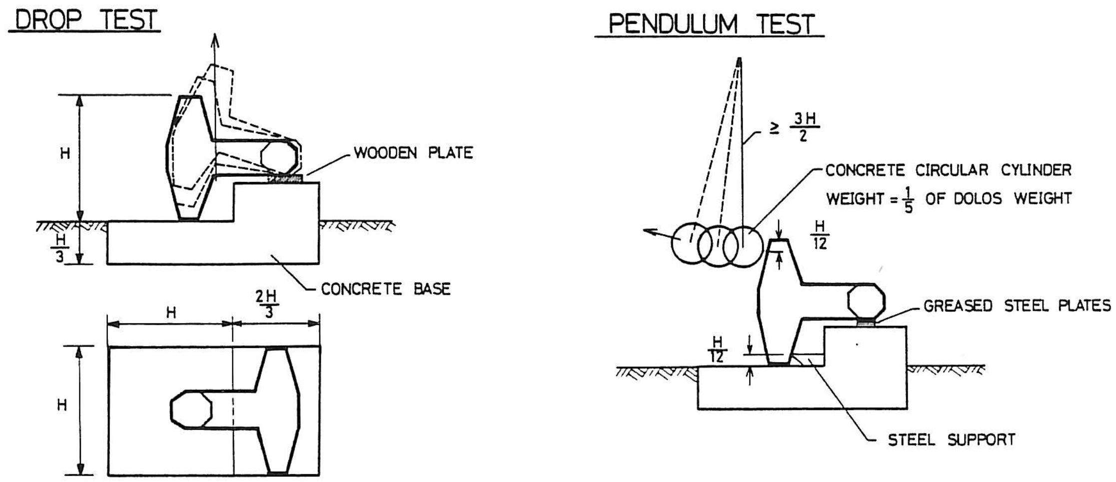
$$\frac{\sigma}{m V^2 L^{-3}} = \text{function of} \left(\frac{E L^3}{m V^2}, \frac{m}{\rho L^3}, \nu \right)$$

By applying a constant ratio $\frac{m}{\rho L^3}$ and neglecting influences from variation in ν we get:

$$\frac{\sigma}{m V^2 L^{-3}} = f \left(\frac{E}{\rho V^2} \right)$$

Similarity approach

Two different types of tests for Dolosse were set up as shown on the figure. A drop test, which simulates the wave introduced rocking of the unit and a pendulum test, which simulates the impact from missiles, that is pieces of broken units that are thrown around by the waves.



Drop and pendulum tests

The formulae for the two tests are as follows:

DROP TEST FORMULA

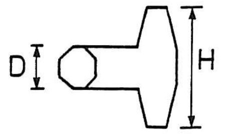
$$\frac{\sigma}{MghH^{-3}} = C\,\frac{1+r}{r^2}\sqrt{\frac{E}{\rho gh}} \qquad (0.3 \leq r \leq 0.4)$$

PENDULUM TEST FORMULA

$$\frac{\sigma}{mghH^{-3}} = K\,\frac{1}{r^3}\sqrt{\frac{E}{\rho gh}}$$

h= LIFTED HEIGHT OF CENTRE OF GRAVITY

$r = \frac{D}{H}$, WAIST RATIO

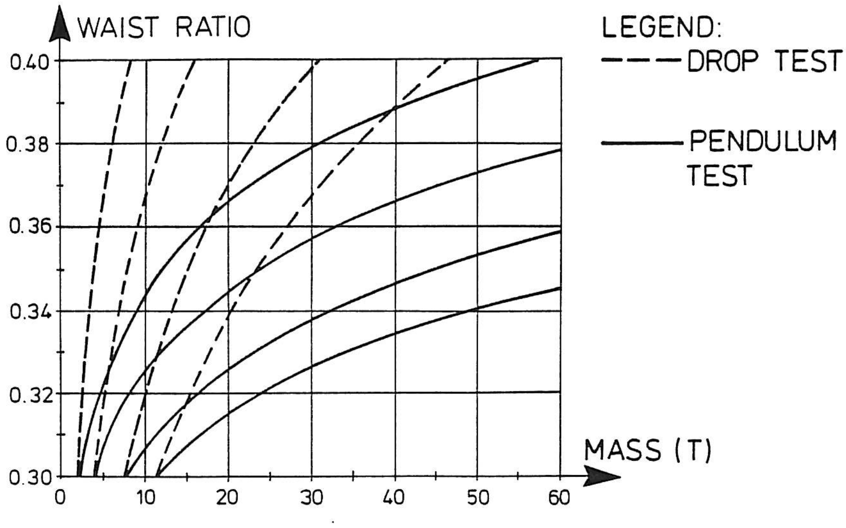


Formulae for drop and pendulum tests for Dolosse

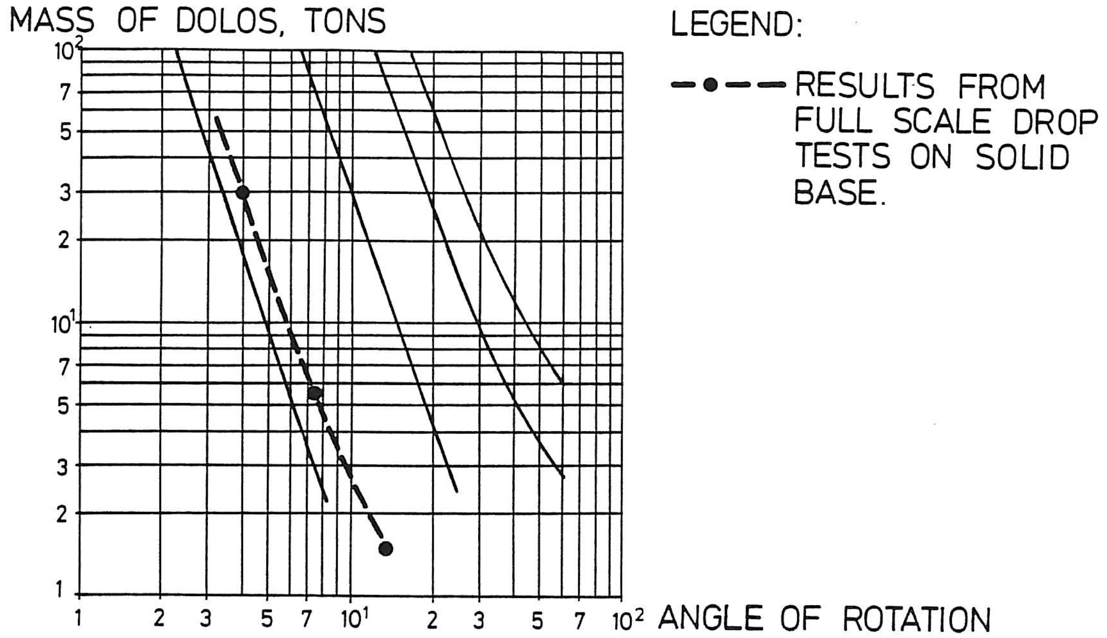
They represent a first approximation as they are derived partly from elasticity theory partly from simple beam theory.

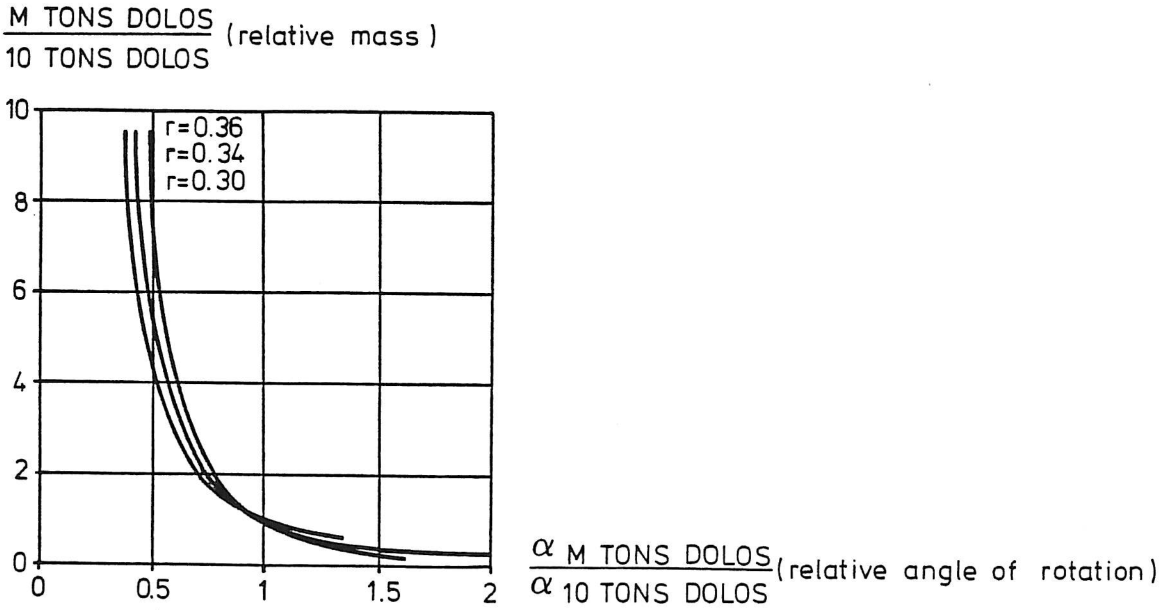
Tests have been performed with unreinforced and reinforced Dolosse ranging from 1.5 to 30 t.

The test results with unreinforced units confirmed the theoretical formulae. The relationship between the size and the relative strength of the units can then be illustrated, for example by iso-stress curves shown in the figures.



EXAMPLES OF ISO-STRESS CURVES FOR DOLOS UNITS WITH THE SAME ANGLE OF ROTATION.





EXAMPLES OF ISO-STRESS GRAPHS FOR ROCKING UNREINFORCED DOLOSSE OF IDENTICAL CONCRETE. WAIST RATIOS 0.30 - 0.36

The results from the full scale drop tests with ordinary unreinforced units followed the dotted curve. Which curve to follow for a real breakwater design situation can be decided only by establishing a relationship to prototype data as follows:

1. HYDRAULIC MODEL TESTS

INPUT: WAVE CLIMATE

HYDRAULIC DAMAGE CRITERION

MODEL ARMOUR UNITS (WAIST RATIO, r_m)

OUTPUT: MASS OF UNIT UNDER DESIGN, M_1.

2. PROTOTYPE EXPERIENCE + DROP TEST FORMULA

INPUT: PROTOTYPE DATA (M_2 , r_2 , σ_2 , E_2 , ϱ_2) FOR ARMOUR

DESIGNED TO SAME HYDRAULIC DAMAGE CRITERION

AND WHICH HAS WITHSTOOD DESIGN WAVE CONDITONS

$$\frac{\sigma_1}{\sigma_2} = \frac{1 - 1.055\, r_1}{1 - 1.055\, r_2} \left(\frac{r_2}{r_1}\right)^{0.214} \left(\frac{M_1 E_1 \varrho_1^2}{M_2 E_2 \varrho_2^2}\right)^{0.167}$$

OUTPUT: WAIST RATIO OF UNIT UNDER DESIGN, r_1.

3. CONTROL

IF HYDRAULIC STABILITY OF UNITS HAVING WAIST RATIOS r_1 AND r_m IS DIFFERENT NEW MODEL TESTS MUST BE PERFORMED AND DESIGN PROCESS REPEATED.

Similarity design process

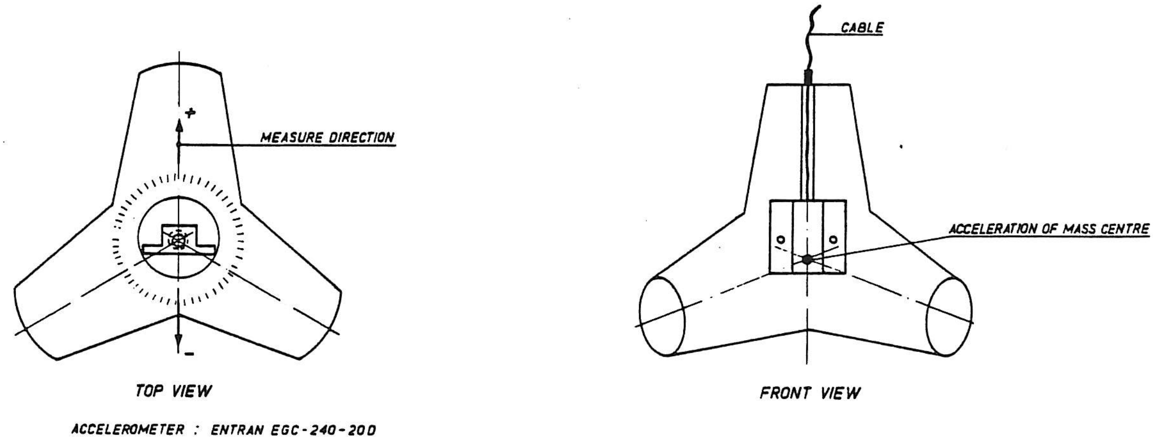
Other full scale tests are cube impact tests by M.G.A. Silva (ref. 6).

10. ad. 3. Model tests for the assessments of static and dynamic loads on armour units represent a more direct method than the similarity method.

The following techniques can be used:

1. Determination of movements by photo/video and/or by means of accelerometer gauges in the units.
2. Correct scaling of material characteristics of model armour units.
3. Determination of forces by strain gauges mounted on model armour units.

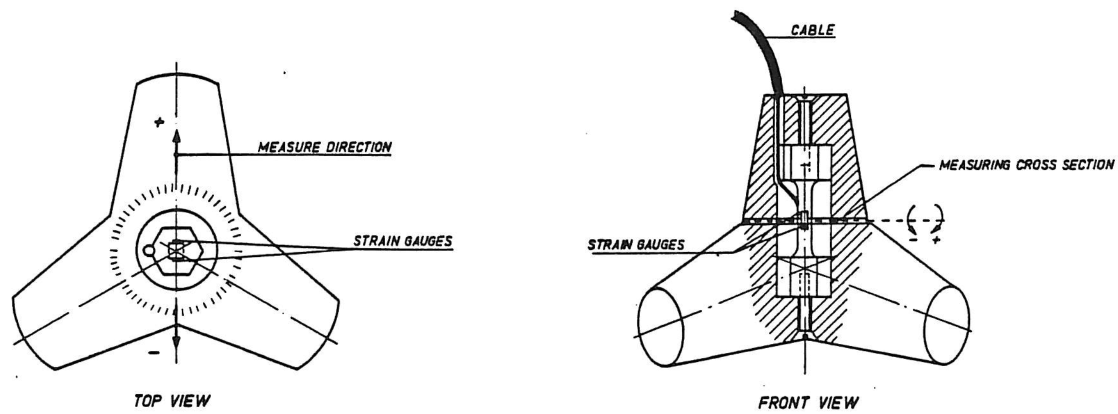
Photo (single frame) and video technique fail to give information on rocking in the splash zone. It is very difficult to arrive at good estimates on forces from recordings of movements.



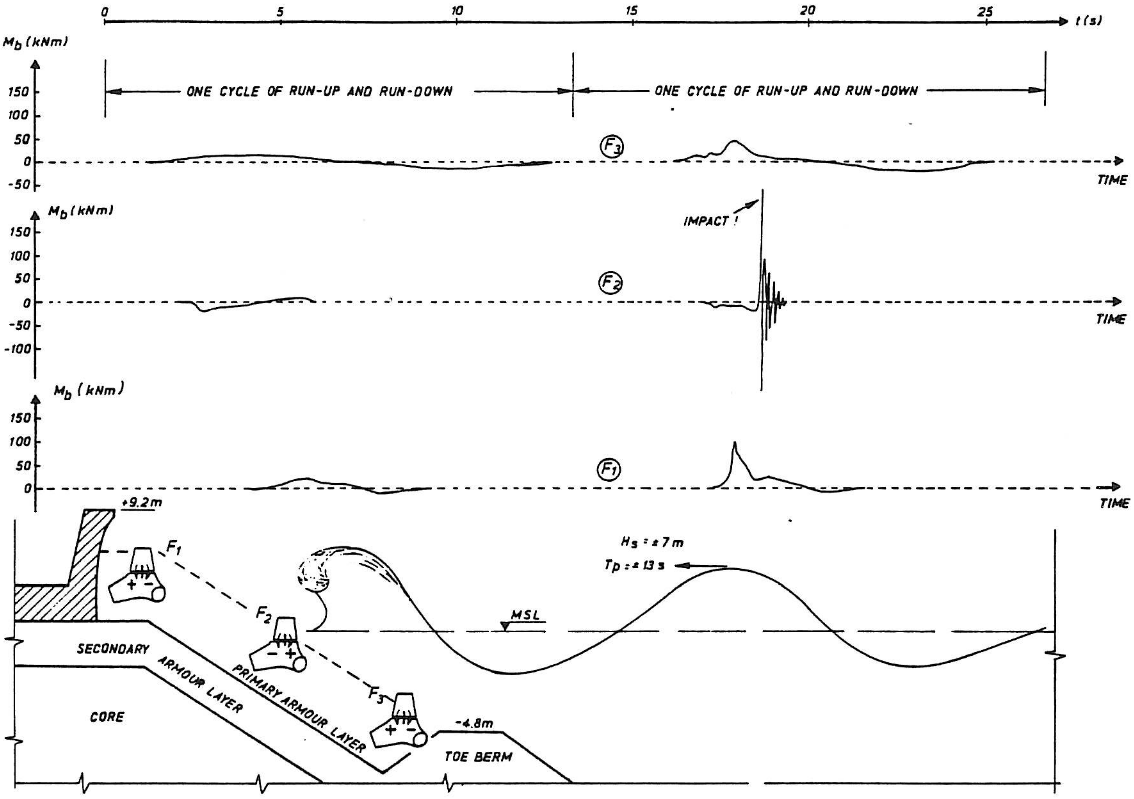
Tetrapod with accelerometer for acceleration measurements
Delft Hydraulics Laboratory

The use of correctly scaled model concrete will show if the strength of the units is sufficient, but more detailed quantitative information on the loads cannot be obtained. Reference is given to the work of Gerry Timco (ref. 7, 8).

Strain gauge technique is useful. However, the spread in load conditions makes it necessary to use either a large number of instrumented units or a large number of tests to obtain good estimates.



Tetrapod with strain gauges instrumented in one leg for bending moment measurements
Delft Hydraulics laboratory



Typical example of the simultaneously recorded time dependent and analoque bending moment signals emitted by the three instrumented units
Delft Hydraulics laboratory

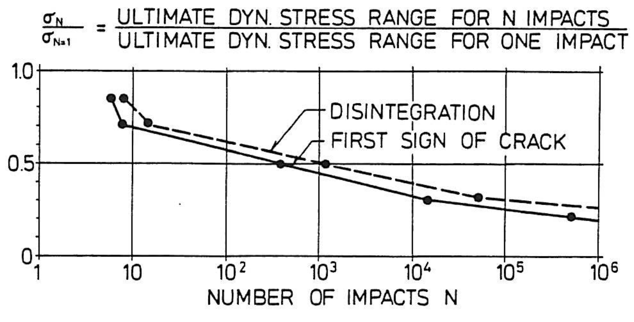
11. ad. 4. Prototype instrumentation of armour units should be implemented in some new structures, where also wave gauges are installed.

    There is still a long way to go before we can obtain good estimates of the load in individual armour units which are necessary as input in a design process.

FATIGUE

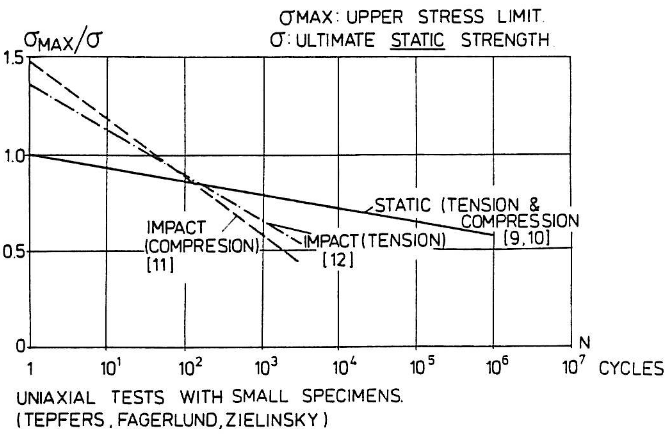
12. Since armour units are exposed to repeated loads and since concrete does show significant fatigue, this effect must be implemented in a design method.

    The following Wöhler diagram shows the results from repeated impact loading of 200 kg unreinforced Dolosse made of fly ash concrete, (height 0.8 m, trunk diameter 0.3 m). The test set up compared to the pendulum test mentioned above.



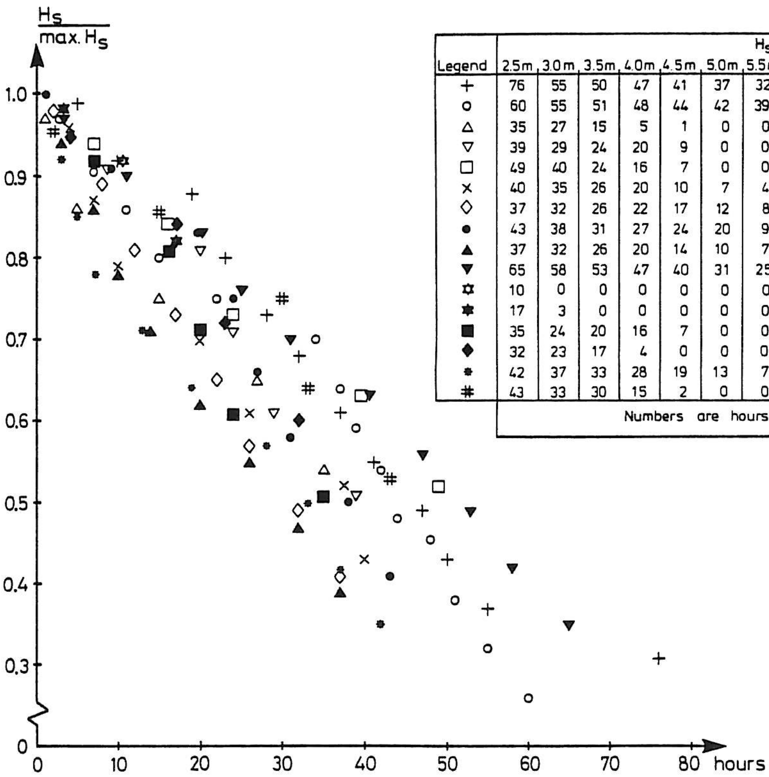
FATIGUE. IMPACT LOADED FLYASH CONCRETE DOLOSSE. FLEXURAL STRESS
(PRELIMINARY RESULTS, BURCHARTH, 1983)

Uniaxial fatigue test results with small specimen (diameter 74 mm) are in fairly good agreement with the Dolosse results (flexural strength), although not directly comparable (ref. 9, 10, 11, 12).



Fatigue uniaxial tests

Fatigue effect can be implemented in a probabilistic design procedure by evaluating the fatigue life according to the Palmgren - Miner hypothesis if the wave load history is specified. Information on the persistance of the storms is necessary. The simple parameterisation of persistance proposed in the figure might be applicable in this respect.



Legend	$H_s \geq$ 2.5m	3.0m	3.5m	4.0m	4.5m	5.0m	5.5m	6.0m	6.5m	7.0m	7.5m	8.0m	8.5m	9.0m	max. H_s m
+	76	55	50	47	41	37	32	28	23	19	10	5	0	0	8.11
○	60	55	51	48	44	42	39	37	34	22	15	11	7	3	9.32
△	35	27	15	5	1	0	0	0	0	0	0	0	0	0	4.64
▽	39	29	24	20	9	0	0	0	0	0	0	0	0	0	4.92
□	49	40	24	16	7	0	0	0	0	0	0	0	0	0	4.78
×	40	35	26	20	10	7	4	0	0	0	0	0	0	0	5.72
◇	37	32	26	22	17	12	8	2	0	0	0	0	0	0	6.15
●	43	38	31	27	24	20	9	1	0	0	0	0	0	0	6.03
▲	37	32	26	20	14	10	7	3	0	0	0	0	0	0	6.37
▼	65	58	53	47	40	31	25	20	11	3	0	0	0	0	7.19
✡	10	0	0	0	0	0	0	0	0	0	0	0	0	0	2.73
✶	17	3	0	0	0	0	0	0	0	0	0	0	0	0	3.06
■	35	24	20	16	7	0	0	0	0	0	0	0	0	0	4.90
◆	32	23	17	4	0	0	0	0	0	0	0	0	0	0	4.19
✱	42	37	33	28	19	13	7	5	3	0	0	0	0	0	7.06
#	43	33	30	15	2	0	0	0	0	0	0	0	0	0	4.67

Numbers are hours where H_s is exceeded.

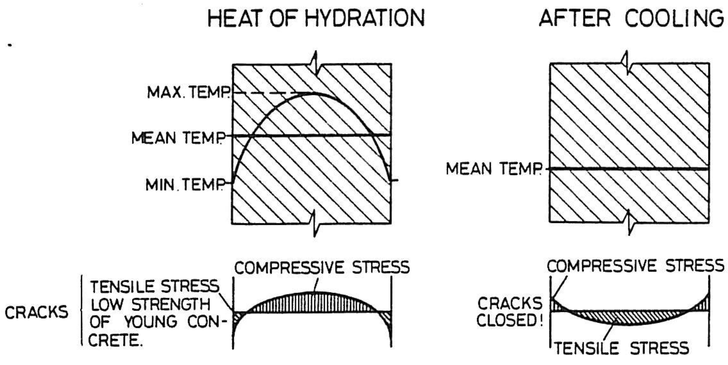
Example of persistance analysis
Raw data Delft Hydraulics Laboratory. Method by H.F. Burcharth

The conventional theories (elastic, plastic, fracture mechanics) are not able to explain the behaviour of concrete. The Continuous Damage Theory is the most promising in this respect (ref. 13, 14, 15).

THERMAL STRESSES

13. During the curing of the concrete the heat of hydration will increase the temperature. Because of the fairly low conductivity of concrete and because of the relatively poor insulation of the formwork a higher temperature will be reached in the centre part of the body than at the surfaces. The temperature difference will create different thermal expansion, but because of the coherence, the various parts of the body are not free to move and thus stresses are created.

The bigger the distance from the centre to the surface of the body the bigger the temperature difference and the stresses will be.

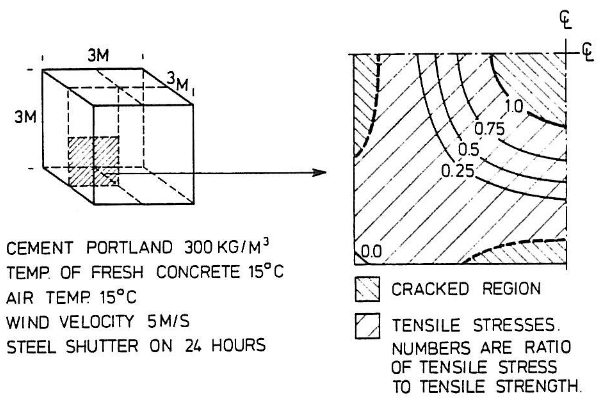


Thermal stresses

Also a high cement content will increase the stresses. The problem has been known and has been well handled for years in relation to, for example, large dams, where cooling systems, low heat cement, etc. are used. It is only few years ago that the question about thermal stresses and cracks was related to concrete armour units, although the size of some of these units and the fact that they are usually unreinforced should have led to thermal crack investigations long time ago.

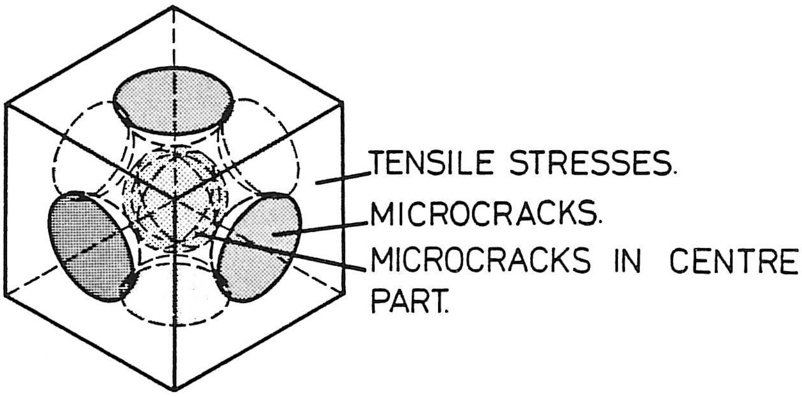
Usually a cement content of 300-400 kg/m^3 is used, as we do not want to go lower because a good long term durability is wanted and also a fast development of strength so that removal and re-use of the rather expensive forms are possible shortly after the pouring of the concrete. The cyclus time varies from 5 hours up to 2 days dependent on the type of unit and the knowledge of the engineers.

Unfortunately it is not possible to see thermal cracks because they will close at the surface after cooling off. The thermal stresses can be calculated from data on concrete mix, formwork, climate, and cyclus time. The figure shows an example of such a calculation for a cube.



THERMAL STRESSES IN A 70T CUBE 100 HOURS AFTER CASTING
(BKI-INSTITUTTET COPENHAGEN AND BURCHARTH, 1982)

Such a cube will have no visible sign of damage, but it will be fragile as only a part of the concrete will retain the full strength.

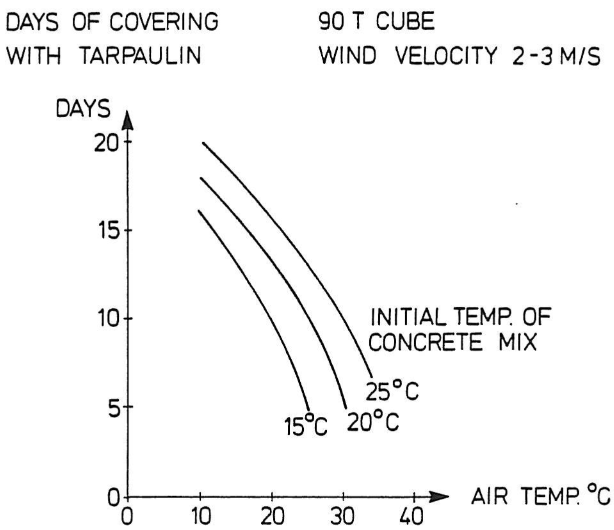


Thermal stresses and cracked regions in a cube after cooling

The centre region and some parts of the surface regions will be full of microcracks and the rest of the volume will be in tension. This means that not only the strength of the block is reduced but also the fatigue life and resistance against deterioration.

On sites where sufficient fresh water is lacking salt water is used for the concretes and this will increase the heat and thereby the thermal stresses.

Measures to prevent thermal stresses are well known, but they all involve drawbacks. The use of low heat cement or retarder slows down production, the use of less cement reduces the surface resistance and the long term durability, the cooling of aggregates and water is expensive and impossible in some places, and the use of insulation during the curing complicates the production. This is illustrated in the figure, which shows an example of a diagram by BKI-Instituttet and Burcharth for determining the number of days where insulation must be kept on a 90 t cube of conventional concrete to prevent thermal cracking. It is seen that approximately 15 days are necessary, which again demands 300-1000 insulation sets, depending on the size of the job.

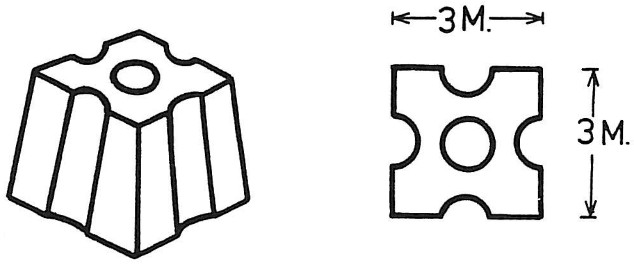


EXAMPLE OF DIAGRAM TO DETERMINE DURATION
OF INSULATION DURING CURING.
(BKI-INSTITUTTET COPENHAGEN AND BURCHARTH, 1982)

What is our experience? It is known that in the case of traditional concretes thermal cracking will not occur if the temperature difference does not exceed 20°C. As a rule of thumb we also say that thermal cracking will not occur if the surface to surface distance is less than approximately 1 meter. In relation to armour units it means that only units bigger than 3 to 10 tons (depending on shape) will suffer from thermal cracking if no measures are taken. This again means that the problem exists in nearly all major rubble mound breakwaters with concrete armour.

It is very easy to check if there is a problem by placing thermocouples in the form and from the temperature readings check if the temperature difference exceed 20°C. Thermocouples are very cheap and reliable now-a-days, so there is no excuse for not implementing this temperature check in the traditional checking procedures at the sites.

In some units it is fairly easy to solve the thermal stress problem by changing the shape slightly. The figure shows how this can be done for a big Antifer cube, simply by making a hole in the middle. In addition, such a modification will increase the hydraulic performance of the armour.



Antifer type Block with hole to reduce
temperature differences during curing

CONCRETE

Concrete has a high compressive strength and a low tensile strength. It is therefore a very brittle material.

In the case of unreinforced armour units it is not the compressive strength but the tensile strength that is the critical parameter. In the specification of concrete much more attention should be paid to this fact.

Besides what is generally known from concrete technology the following results from full scale tests of armour units might be of interest. A very low water cement ratio (< 0.4) obtainable by the use of super-plasticizers and the use of puzzolan cement seem beneficial for the dynamic and static strength. High-strength concretes exhibit only slightly larger impact strength than normal concretes (ref. 3). This is because high-strength concretes are relatively more brittle, as the ratio of tensile to compressive strength is smaller.

Reinforcement

Reinforcing the concrete is the obvious way of improving the strength properties. Both conventional steel bar reinforcement and fibre reinforcement are used.

Results from the full scale static tests and dynamic drop tests with Dolosse in the range 1.5t to 30t show that conventional reinforcement is superior to steel fibres of equal quantity. By using 100-130 kg steel per m^3 concrete, spalling and not cracking seems to be the limiting factor (ref. 3 plus not published results). A steel fibre content less than 70 kg per m^3 does not significantly improve the relevant strength properties compared to unreinforced units.

Fibre is beneficial only in very slender, flexible structural members, not in relatively stiff elements like Dolosse, Tetrapods, etc. Chopped polypropylene fibres (used for example in the SHED-unit, a holowed cube type of unit) might be beneficial in preventing shrinkage cracks from occurring.

Shrinkage cracks of some centimeters' depth have no significant influence on the strength (static and dynamic) of armour units where cross section diameters are bigger than 1 m. However, such cracks are harmful with respect to the long term durability.

Corrosion

Corrosion has prevented many coastal engineers from using steel reinforcement. Research on corrosion is intense and promising. Results obtained so far at the Danish Corrosion Centre, Copenhagen (F. Grønvold), show that the use of fly ash reduces corrosion, and that high densified concrete with a substantial content of silica dust nearly eliminates the risk of harmful corrosion in bars of the sizes used in large armour units.

The influence of crack width on corrosion is still not fully understood. It seems that the width has an influence on the initiation of corrosion only. That is, a small crack width will delay the corrosion, but when corrosion has started the rate seems to be independent of the width. A rough personal estimate is that crack widths smaller than 0.1 mm will delay harmful corrosion some five years compared to crack widths of 0.5 mm, other things equal.

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